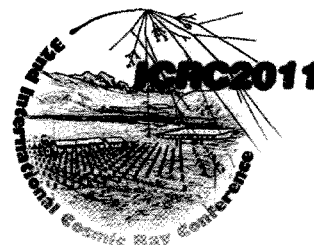


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Fermi LAT Observations of Cosmic-Ray Electrons

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Abstract: We present the results of our analysis of the cosmic ray electron spectrum using more than 20 million electron candidate events above 20 GeV, collected by the Fermi Large Area Telescope in 29 months of science operation. The obtained spectrum is in full agreement with that obtained in the first year of operation. We analyzed the effect of the recently reported broken power law cosmic ray proton spectrum and also discuss the future perspectives for the analysis of high energy cosmic ray electrons with Fermi LAT

Keywords: cosmic ray electrons, gamma-ray telescope

1 Introduction

The Fermi observatory was launched from Cape Canaveral by a Delta-II rocket on June 11, 2008, into a near-circular 565 km orbit with 25.6 inclination. The main instrument, the Large Area Telescope (LAT), is a wide field-of-view, imaging high energy telescope for detecting celestial gamma-rays [1]. However, in the early stages of its design it was recognized that it would be a capable detector of high-energy electrons [2]. High-energy cosmic-ray electrons (hereafter CRE) lose their energy rapidly according to $-dE/dx \sim E^2$ by synchrotron radiation on Galactic magnetic fields and by inverse Compton scattering on the interstellar radiation fields. The typical distance over which a 1 TeV CRE loses half of its total energy is estimated to be 300-400 pc (see e.g. [3]) when it propagates within about one kpc of the Sun. Also, CRE are affected by the propagation processes such as energy-dependent diffusive losses, convective processes in interstellar medium and possible re-acceleration during propagation from the sources. All this makes CRE a unique tool for exploring the nearby Galactic environment.

Recent results on CRE from ATIC [4], PAMELA [5], and PPB-BETS [6] sharply increased interest in this topic. ATIC and PPB-BETS reported an excess of electrons in the range 300 – 700 GeV compared to the background expected from a conventional homogeneous distribution of cosmic-ray sources. The H.E.S.S. team reported a spectrum that steepens above ~ 900 GeV [6], which was confirmed at this Conference by the MAGIC

team [7]. The PAMELA team reports (recently confirmed by the Fermi LAT for an extended energy range[8]) that the ratio of the positron flux to the total flux of electrons and positrons increases with energy above ~10 GeV. This result has significant scientific implications. The Fermi LAT team has reported [9] that the CRE spectrum between 20 GeV and 1 TeV has a harder spectral index (best fit 3.04 in the case of a single power law) than previously indicated, showing an excess of CREs at energies above 100 GeV with respect to most pre-Fermi experiments. This result was extended down to 7 GeV with the statistics collected for the 1st year of Fermi LAT operation in the detailed paper [10]. The present paper summarizes the analysis approach, presents the spectrum obtained for 29 months of observations and analyzes the effect of a broken power law proton spectrum, recently reported by ATIC [11], CREAM [12], and PAMELA [13]. We also discuss the plan and perspectives for the CRE analysis by Fermi LAT.

2 Fermi LAT analysis of CRE

The LAT is a pair-conversion gamma-ray telescope designed to measure gamma-rays in the energy range from 20 MeV to greater than 300 GeV. The LAT is composed of a 4 x 4 array of identical towers that measure the arrival direction and energy of each photon. Each tower is comprised of a tracker and a calorimeter module; the entire LAT is covered by a segmented anticoincidence

detector. The detailed information about LAT design and characteristics can be found in [1].

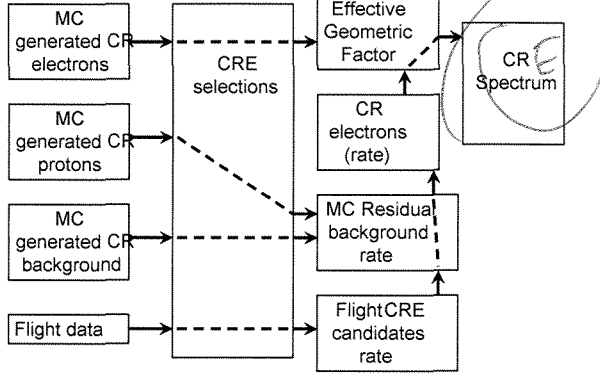


Fig.1 Block-diagram of the CRE analysis. Dashed line means that the operation is applied (e.g. selections applied, or background rate subtracted)

The CRE analysis is based on the gamma-ray analysis and is described in detail in [10]. The main challenge of the analysis is to identify and separate electrons from all other species, mainly CR protons. The analysis involves a trade-off between the efficiency for detecting electrons and that for rejecting hadrons. The hadron rejection must be $10^3 - 10^4$, increasing with energy. The analysis is heavily based on extensive Monte Carlo simulations. These simulations have been used to develop the electron selection algorithms to remove hadron background, and to determine the instrument response functions for CRE analysis including efficiency, effective area and solid angle (effective geometric factor) for spectral reconstruction. The block-diagram of the analysis is given in fig.1. The event selection relies on the capabilities of the tracker, calorimeter and anticoincidence subsystems to discriminate between electromagnetic and hadronic event topologies. The shapes of hadronic showers differ significantly from EM showers. The most powerful separators are the comparative lateral distributions; however we use more than 20 variables in all stages of the analysis. The use of variables that map the distribution of the tracker clusters around the main track, second-order moments of the energy distribution around the shower axis in the calorimeter, distribution of energy and hits in the anticoincidence detector provide the hadron rejection at the level of a few hundred to a thousand. The remaining necessary rejection power is obtained by combining two probability variables from training classification trees (CT) to distinguish between electromagnetic and hadron events (fig.2).

The electron energy reconstruction is performed using the algorithms developed for the photon analysis [1]. These algorithms are based on comprehensive simulations and validated with the beam test data [14]. For each event, the energy is reconstructed by three different energy reconstruction algorithms (a parametric correction, a maximum likelihood fit, and a three-dimensional fit to the shower profile), and the best method is then selected by means of a CT analysis. The energy resolution corresponding to a 68% half-width containment is about 6% at

7 GeV and increases with energy reaching 15% at 1 TeV. The instrument acceptance for electrons (or effective geometric factor EGF) is defined as a product of the instrument field-of-view and its effective area. It is calculated using a Monte Carlo simulation of an isotropic electron spectrum. The EGF has a peak value of $\sim 2.8 \text{ m}^2 \text{ sr}$ at an energy around 50 GeV and decreases to about $1 \text{ m}^2 \text{ sr}$ at 1 TeV.

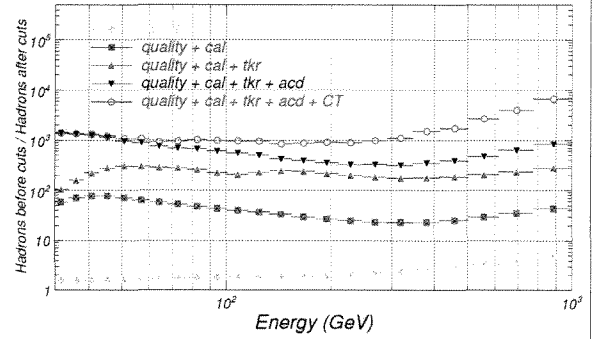


Fig.2 Hadron rejection power for different selection steps. All LAT subsystems (tracker, calorimeter and anticoincidence detector) contribute to the overall rejection, with final rejection provided by the CT

The approach to the hadron background removal is illustrated in fig.1. We generate Monte Carlo simulations for the incident cosmic ray protons, and apply the CRE selections, exactly the same as for the flight data. After scaling the simulation to a realistic proton flux, we obtain the rate of simulated proton background events and the rate of flight electron candidates. Subtracting the former from the latter, we calculate the rate of electron events. Applying the effective geometric factor (which is energy dependent) we calculate the resulting CRE spectrum. By varying the spectral parameters of the proton flux in accordance with published results, we estimate a systematic error originating from an uncertainty in knowledge of the proton spectrum. Special attention in present analysis was given to account for possible features in the CRE spectrum which can be introduced by the broken power law proton spectrum. Due to high event counting statistics (more than 3,000 electron events in the highest

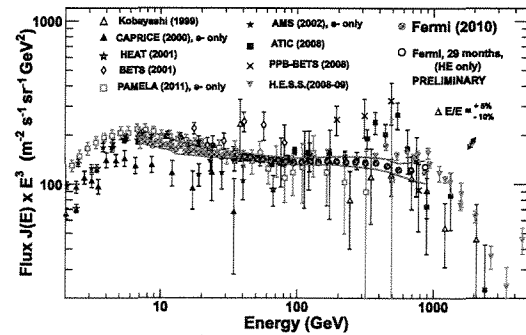


Fig.3 Cosmic-ray $e^+ + e^-$ spectrum as measured by Fermi LAT (filled circles – as published in [10] and open circles – 29 months spectrum), along with other recent high energy results

energy bin), our resulting uncertainty is dominated by systematic uncertainty. One of its main sources is the imperfect knowledge of the EGF. This comes from the fact that the simulations we use for the calculation of the EGF cannot perfectly reproduce the topological variables used in the analysis. The assessment of the analysis systematic uncertainties is described in [10].

The CRE spectrum obtained for 29 months of the Fermi LAT operation on orbit, along with other results, is shown in fig.3. The systematic errors, shown as a band in this figure, also contain contribution from an assumed broken power law proton spectrum; however this contribution was found to be negligible (a few percent in respect to the total systematic error) and not affecting the spectral shape. The spectrum fully agrees with that published in [10] and demonstrates the stability of our measurements.

Fermi LAT CRE spectrum has been widely discussed in numerous papers (e.g. [15] and references therein). Within the systematic errors the entire spectrum from 7 GeV to 1 TeV can be fitted by a power law with spectral index 3.08 ± 0.05 . However, the measured spectrum suggests some spectral flattening at 70-200 GeV and a noticeable excess above 200 GeV as compared to power-law spectral fit. One of viable possibility to explain our spectrum would be to introduce of an additional leptonic component with a hard spectrum. This explanation is motivated by the rise in the positron fraction reported by PAMELA [5] and confirmed by Fermi LAT [8]. The nature of these features is still unclear; it can be a contribution from nearby sources, either astrophysical or “exotic”, or created during acceleration in the sources or during propagation.

3 CRE Anisotropy

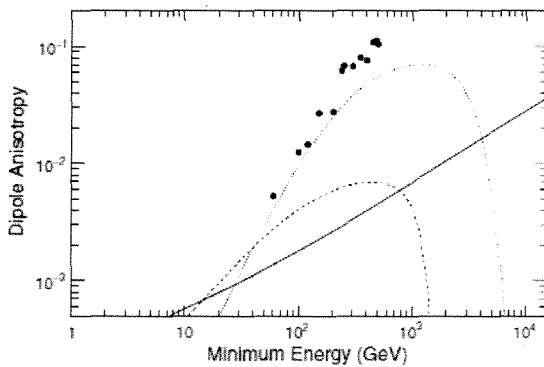


Fig.4 Dipole anisotropy vs. the minimum energy for GALPROP (solid line), Monogem source (dashed line), and Vela source (dotted line). The 95% CL from our data is shown by filled circles [10]

Available high statistics of CRE provides a unique opportunity to search for directional anisotropy in their flux. This study can provide information on local cosmic ray sources and their distribution in space, cosmic ray propa-

gation environment, heliospheric effects, presence of dark matter clumps, etc. The first Fermi LAT result on this was published in [16], where the analysis approach is given in full detail. We analyzed more than 1.6 million primary electrons with energies above 60 GeV, observed by the LAT during its first year of operation. The search was performed using two independent and complimentary techniques, both providing a null result. The upper limits on a fractional anisotropic excess ranged from a fraction of a percent to roughly one, for the range of minimum energies and angular scales considered. A detailed study of the dipole anisotropy has been also performed, and upper limits ranging from $\sim 0.5\%$ to $\sim 10\%$, depending on the energy, have been set (fig.4). Our upper limits on the dipole anisotropy were compared with the predicted anisotropies from individual nearby pulsars and from dark matter annihilations. In all cases, our upper limits lie roughly above the predicted anisotropies.

4 Future perspectives in CRE analysis with Fermi LAT

We expect important new results from Fermi LAT on CRE with the use of the new Fermi LAT analysis, currently under development. It will have an improved event pattern recognition, better agreement between the flight data and Monte Carlo, correction for the events with signal pile up and accidental coincidences, and improved efficiency to gamma rays. It will also have improved energy reconstruction at high energy with the goal to extend the energy range up to a few TeV.

Detailed CRE spectral structure. It was reported in [10] that in our analysis the energy resolution can be significantly improved by selecting events with longer path in the LAT, e.g. selection of events with pathlength more than 12 radiation lengths in the calorimeter (16 radiation lengths in average for the whole LAT). This selection provides energy resolution better than 5%, but the statistics reduces by a factor of ~ 20 . With the new analysis and more than 3 years of LAT operation we will have more reliable reconstruction of the spectral shape with “fine” energy binning, allowed by the long path event selection. As an example: the expected statistics for such selection in a 100-GeV-wide bin at 1 TeV is ~ 100 electrons per 3 years (10% statistical error)

Spectrum above 1 TeV. H.E.S.S. reported a spectral fall at around 1 TeV with the change of slope from 3.0 to 4.1 [6], confirmed by MAGIC [7]. This is a fundamental issue, and we hope that LAT will be able to study the CRE spectrum above 1 TeV with new analysis. Expected statistics from 1 to 3 TeV is $\sim 3,500$ electrons for 3 years (for the standard analysis), if the spectral index does not change, and will decrease to $\sim 2,800$ if the spectral index above 1 TeV is 4.1 as reported by H.E.S.S.

CRE anisotropy. We already published anisotropy limits on the CRE flux. Currently the Fermi LAT sensitivity is

approaching the range expected by the theoretical models, both for dark matter and for pulsars.

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Fermi LAT observations of cosmic-ray electrons

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***NASA Goddard Space Flight Center and
University of Maryland***

for the Fermi LAT Collaboration



The Fermi Gamma-Ray Space Telescope: launched on June 11, 2008

- Large Area Telescope (LAT)
(20 MeV – >300 GeV)
- Gamma-ray Burst Monitor (GBM)
(8 keV – 40 MeV)



***Spacecraft with LAT and GBM
before shipping to KSC***

Alexander Moiseev

32-th ICRC

Beijing, China, August 2011

LAT collaboration

France

- ✧ IN2P3/LLR Ecole Polytechnique
- ✧ IN2P3/CENBG Bordeaux
- ✧ IN2P3/LPTA Montpellier
- ✧ CEA/Saclay
- ✧ CESR Toulouse



Germany

- ✧ MPI fuer extraterrestr. Physik, Garching



Italy

- ✧ INFN Bari, Padova, Perugia, Pisa, Rome, Trieste, Udine
- ✧ ASI
- ✧ INAF-IASF



Japan

- ✧ Hiroshima University
- ✧ ISAS/JAXA
- ✧ Tokyo Institute of Technology



Spain

- ✧ IEEC-CISC, Barcelona



Sweden

- ✧ Royal Institute of Technology (KTH)
- ✧ Stockholm University

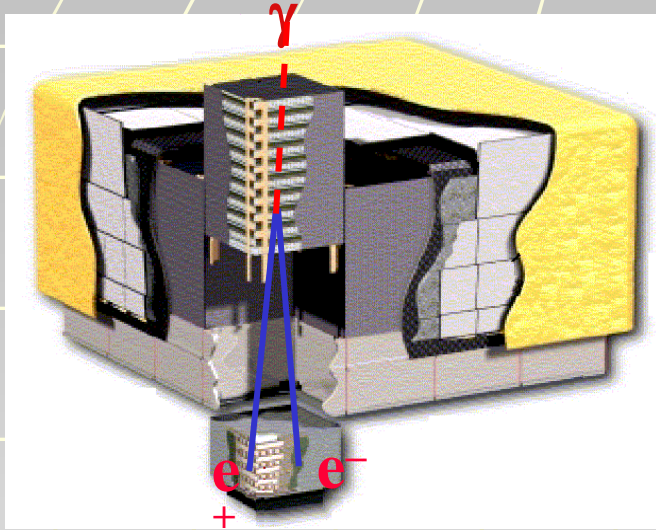


United States

- ✧ Stanford University (HEPL/Physics, SLAC, KIPAC)
- ✧ UC Santa Cruz
- ✧ Goddard Space Flight Center
- ✧ Naval Research Laboratory
- ✧ Sonoma State University
- ✧ Ohio State University
- ✧ University of Washington
- ✧ University of Denver
- ✧ Purdue University – Calumet



Designed as a gamma-ray instrument, the LAT is a capable detector of high energy cosmic ray electrons



- The LAT is composed of a 4x4 array of identical towers. Each tower has a Tracker and a Calorimeter module. Entire LAT is covered by segmented Anti-Coincidence Detector (ACD)

- The electron data analysis is based on that developed for photons. **The main challenge is to identify and separate electrons from all other charged species, mainly CR protons** (for gamma-ray analysis this is provided by the Anti-Coincidence Detector)
- The hadron rejection power must be $10^3 - 10^4$ increasing with energy
- Another challenge – assessment of systematic errors : statistical errors are very small

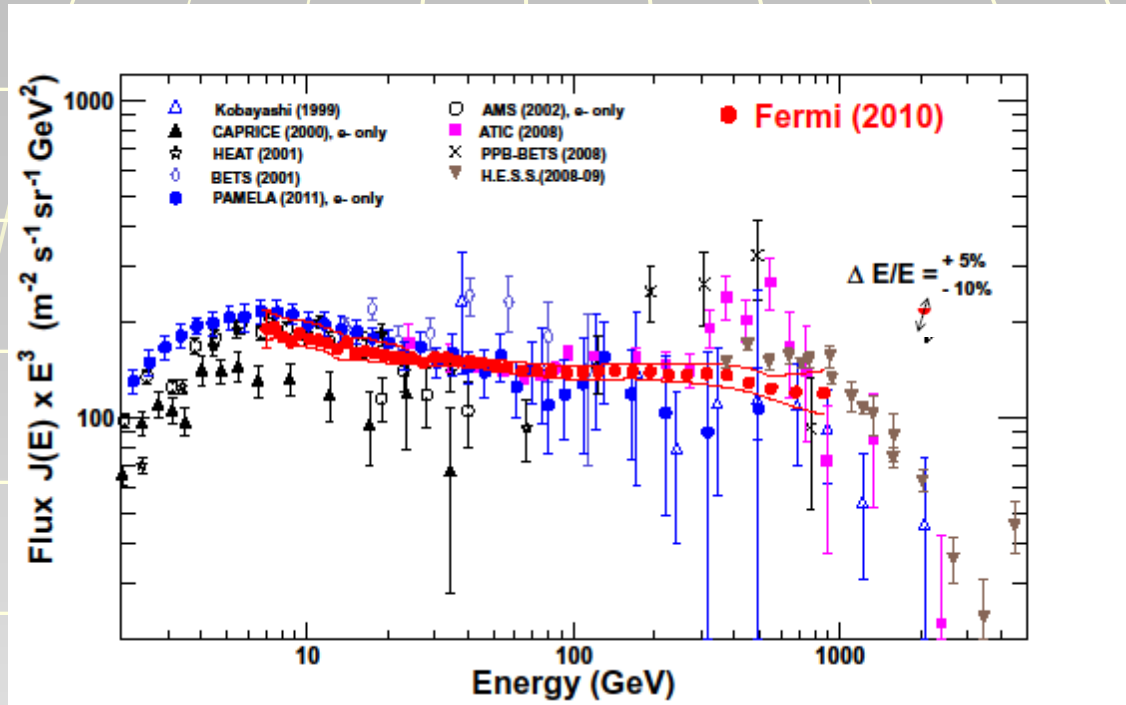
Why electrons?

- Due to their low mass high energy cosmic ray electrons (CRE) lose their energy rapidly (as $-dE/dt \sim E^2$) by synchrotron radiation on Galactic magnetic fields and by inverse Compton scattering on the interstellar radiation field
- The life-time of 1 TeV electron due to these energy losses is $\sim 10^5$ yr
- The typical distance over which a 1 TeV electron loses half of its energy is ~ 300 -400 pc



- Observation of such HE CRE would imply existence of a nearby source of TeV electrons
- This makes CRE a unique tool for probing nearby Galactic space (Galactic halo is ~ 40 kpc diameter, ~ 4 kpc thick)

Currently available results on high energy CRE



Fermi LAT results:

- PRL 102, 181101, 2009 reported the spectrum from **20 GeV to 1 TeV**, taken in the first 6 months of operation. Total statistics 4.7M events. **Most cited Fermi LAT paper so far (over 450 times)**
- PRD 82, 092004, 2010: spectrum from **7 GeV to 1 TeV**, collected in the 1st year. Total statistics 7.95 M events. More than 1000 events in highest energy bin (772 – 1000 GeV)

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Ackerman et al., Fermi LAT Collaboration, Phys. Rev. D82, 092004,
November 2010 (arXiv 1008.3999)

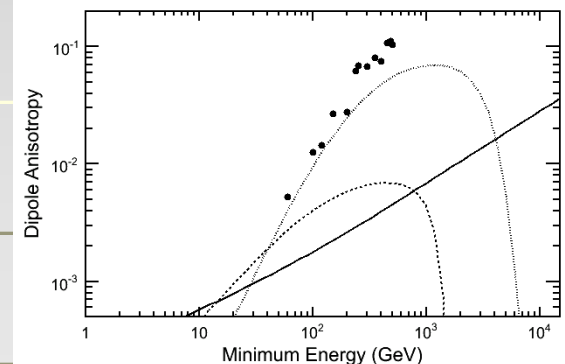
CR Electrons Anisotropy

Search for CR electrons anisotropy can provide information on:

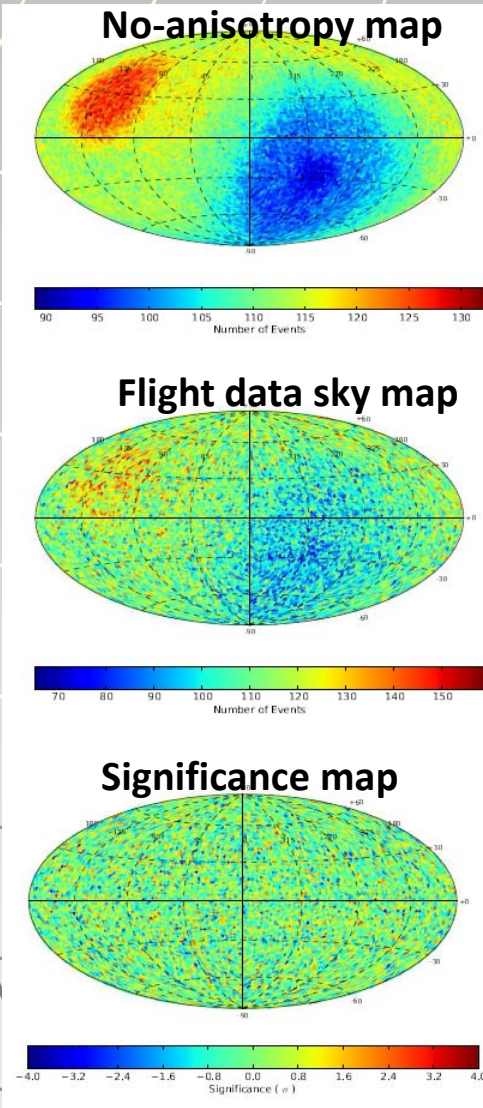
- **Local CR sources and their distribution in space**
- propagation environment
- **heliospheric effects**
- presence of dark matter clumps producing $e^+ e^-$

Result:

- More than 1.6 million electron events with energy above 60 GeV have been analyzed on anisotropy
- Upper limit for the dipole anisotropy has been set to 0.5 – 5% (depending on the energy)
- Upper limit on fractional anisotropic excess **ranges from a fraction to about one percent** (depending on the minimum energy and the anisotropy's angular scale)
- Our upper limits lie roughly on or above the predicted anisotropies



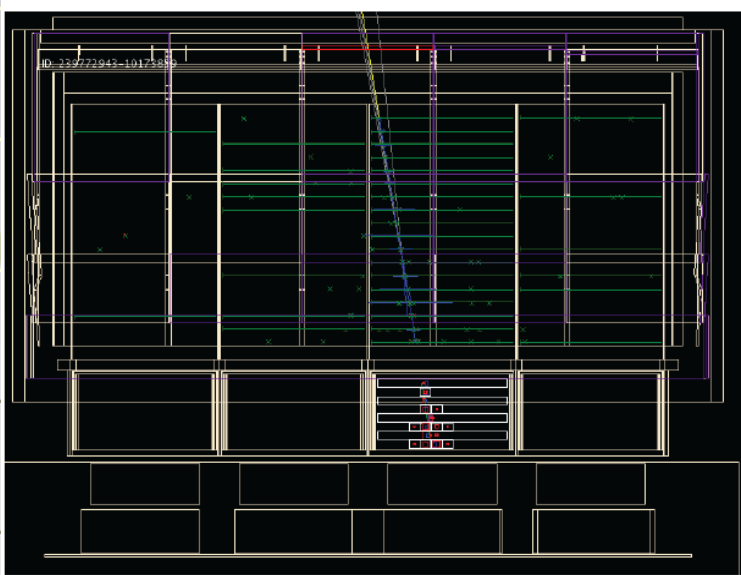
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Dipole anisotropy vs. minimum energy.
Solid line: Galprop spectrum, dashed line – Monogem, dotted line – Vela
Circles: Fermi LAT 95 % CL data



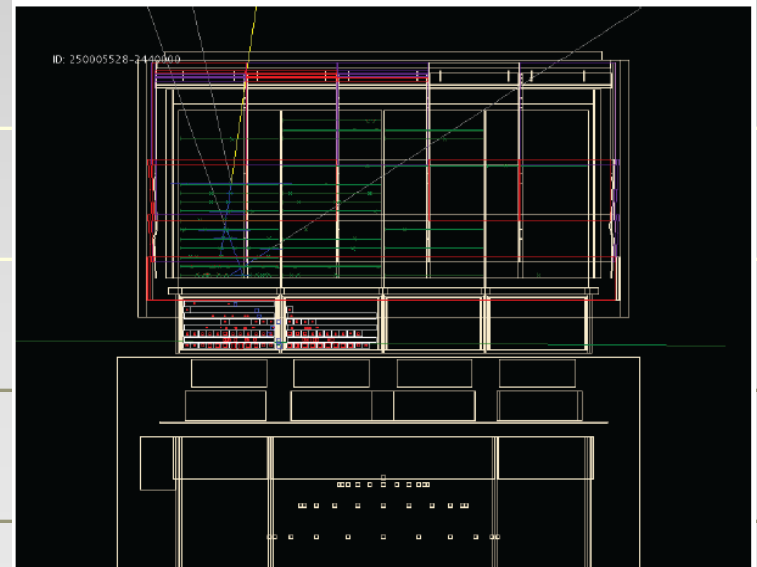
Electron Event Selection in Fermi LAT analysis

- All the LAT subsystems – tracker, calorimeter and ACD contribute to the event selection
- Event selection is based on the difference between electromagnetic and hadronic event topologies in the instrument

Flight event display



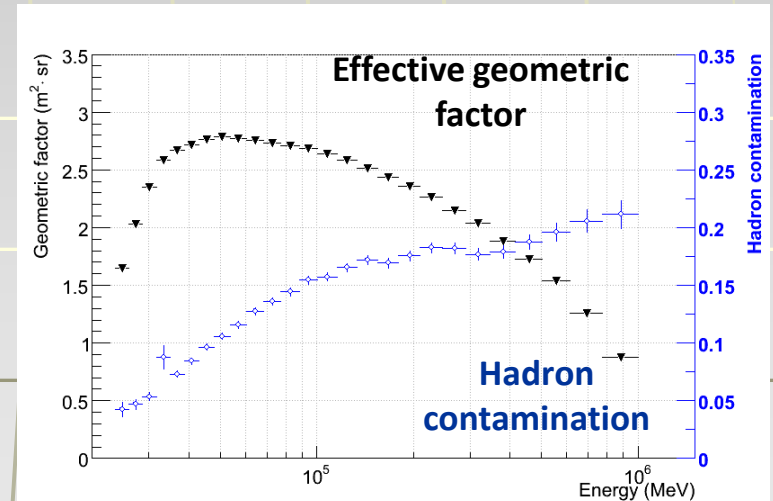
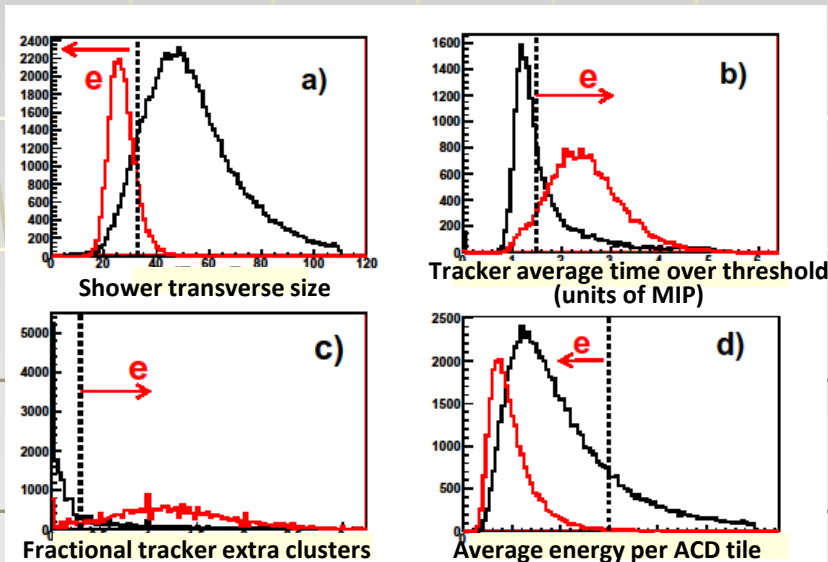
Electron candidate, 844 GeV



Background event, 765 GeV

Electron event selection (cont.)

- Electron event selection is a complicated, highly-optimized process that utilizes numerous physical variables from all 3 LAT subsystems, as well as combined variables calculated with the Classification Tree method
- Most of the selections are energy dependent or scaled with the energy
- The most powerful separators between electromagnetic and hadronic events are the lateral distributions of the shower image

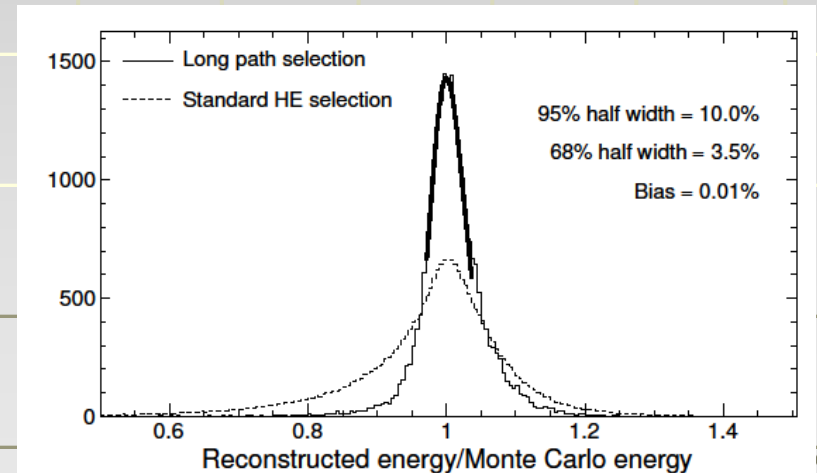
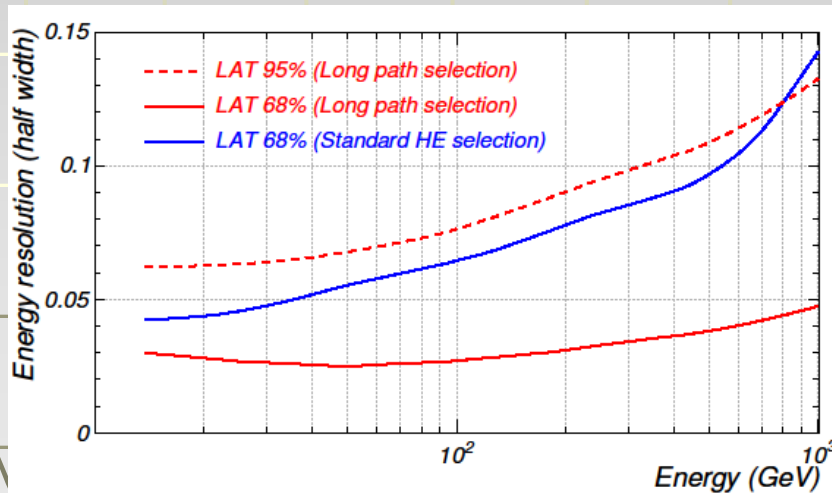


Residual Hadron contamination rate is subtracted from the rate of electron candidate events

Histograms of selected variable distributions for the electron (red) and proton (black) events

Energy resolution

- 6% at 20 GeV, gradually increasing to 13% at 1 TeV (half width for 68% event containment)
- Selecting of the events with long paths in the calorimeter ($> 12 X_0$; average path length $\sim 16 X_0$), the energy resolution becomes better than 5% up to 1 TeV



Comparison of standard and "long path" analysis

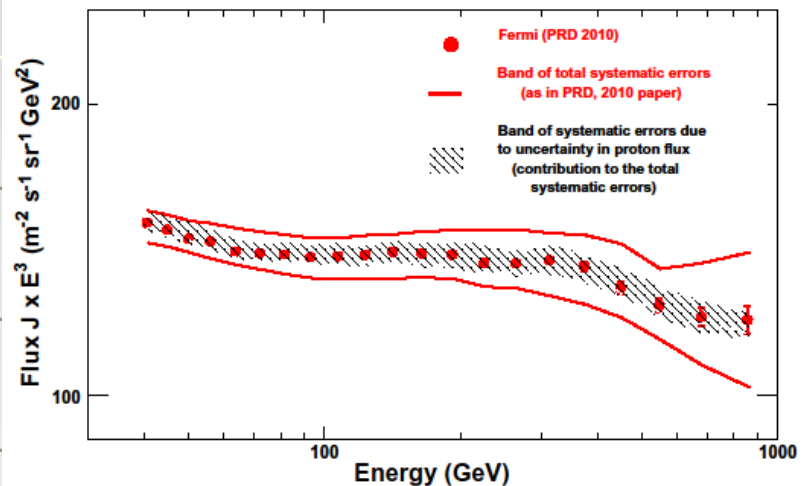
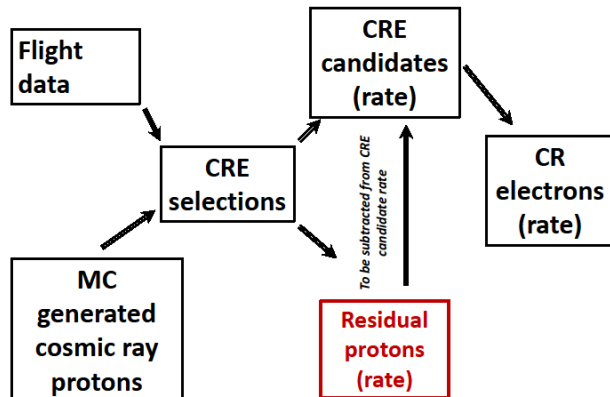
Systematic uncertainties

- Very high event counting statistics → **our result is dominated by systematic uncertainties.**
- **Careful analysis** of contributions to the systematic uncertainty:
 - uncertainty in knowledge of the LAT response (mainly the effective geometric factor, 5-20% increasing with energy)
 - uncertainty of residual hadron contamination (< 5%). **Recently published data on the broken proton spectrum (Pamela, CREAM, ATIC) require to check the effect of the proton spectral break on our reconstructed electron spectrum.**
- Uncertainty in absolute energy scale (+5-10%) is constant with energy and can imply only a rigid shift of the entire spectrum

Correction for the residual hadron contamination with the use of new proton data

- Accurate calculation of the residual (hadron) background assumes good knowledge of the proton spectrum.
- We re-calculated the correction for the background (residual hadrons) with the use of the new proton data with the spectral break at 200-300 GeV and found that its effect on the shape of reconstructed CRE spectrum is negligible (see dashed band on the plot, corresponding to the highest and lowest proton spectra). The upper edge of the band corresponds to the ATIC proton spectrum (index 2.75 below 300 GeV, 2.65 above)

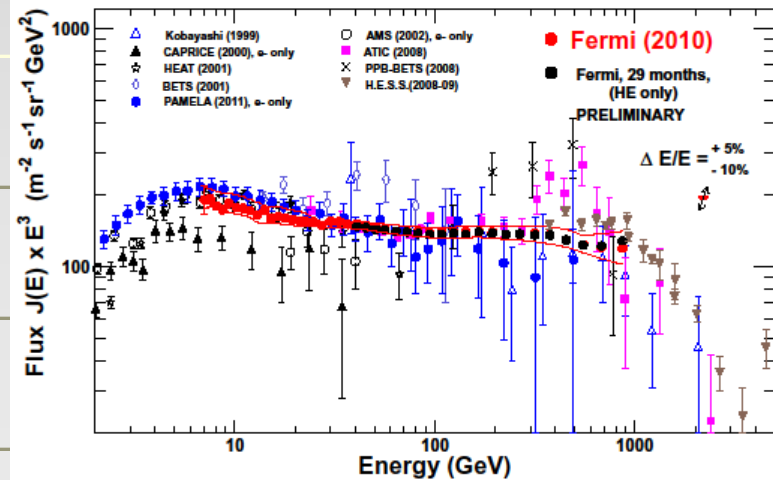
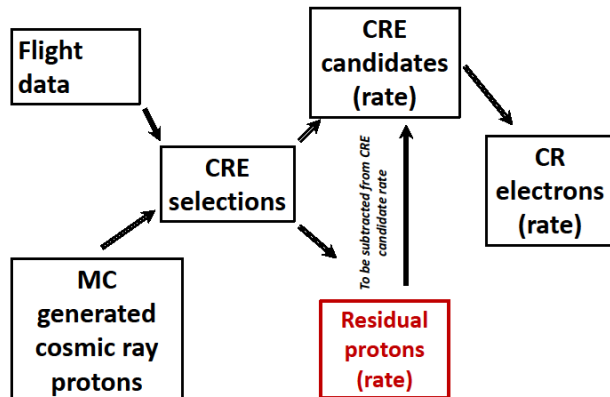
Hadron background removal in Fermi LAT CRE analysis



Correction for the residual hadron contamination with the use of new proton data

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Hadron background removal in Fermi LAT CRE analysis



Interpretation

Conventional (pre-Fermi) model: $e^+ + e^-$ spectrum consists of dominating “primary” (produced in quasi-uniformly distributed distant astrophysical sources, thought to be SNR) e^- , plus contribution from “secondary” e^+ and e^- , produced in interactions of cosmic rays with interstellar matter

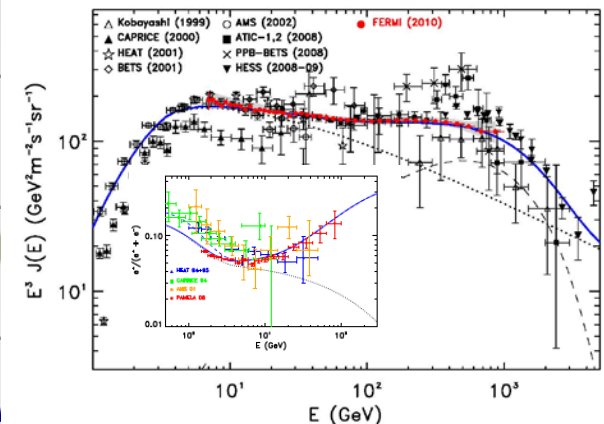
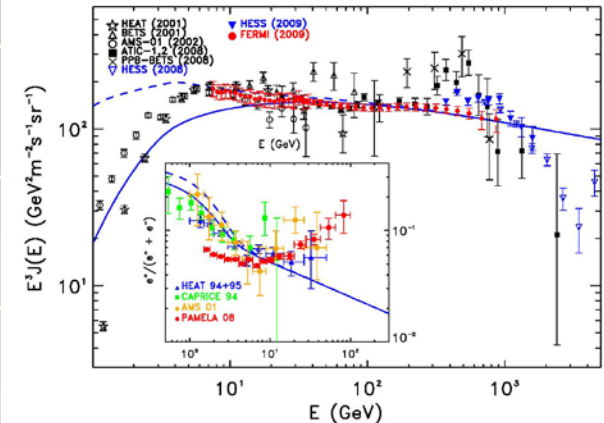
- We were rather successful to fit our first spectrum published in PRL paper (20 GeV – 1 TeV) with a single component (single power law fit).

- With our new spectrum extended down to 7 GeV we tested many combinations of injection spectra, diffusion models and solar modulation. **It appears that the spectral flattening at 20-100 GeV and the softening at ~ 500 GeV cannot be satisfactory fitted by the single component model.**

- Positron fraction, reported by Pamela and **recently confirmed by Fermi LAT** (see talk of *Justin Vandenbroucke* in this conference) cannot be reproduced as well

Conclusion: Fermi LAT electron spectrum cannot be explained within conventional single-component model

Introduction of an additional component of the CRE flux: it is assumed that there is a source of HE $e^+ + e^-$ with hard spectrum, providing equal amount of e^+ and e^- , in order to satisfy raising with energy positron ratio. **This component can be astrophysical or “exotic”, such as dark matter clump**





Future perspectives in CRE analysis with Fermi LAT

1. We expect important new results from Fermi LAT on CRE with the use of the new Fermi LAT analysis called Pass 8, currently under development. It will have an improved event pattern recognition, better agreement between the flight data and Monte Carlo, correction for the “ghost” events, improved efficiency to gamma-rays, etc. It will also have **improved energy reconstruction at high energy with the goal to extend the energy range up to few TeV.**
2. Detailed spectral structure. It was reported in our PRD paper that in our analysis the energy resolution can be significantly improved by selecting events with longer path in the LAT, e.g. selection of events with pathlength more than $12X_0$ in the calorimeter ($16 X_0$ in average for the whole LAT) provides energy resolution better than 5%, but the statistics reduces by a factor of ~ 20 . With the new Pass 8 analysis and 3+ years of LAT operation we will have more reliable reconstruction of the spectral shape. The expected statistics (with “long path” analysis) in a 100-GeV-wide bin at 1 TeV is ~ 100 electrons per 3 years (10% statistical error)
3. Spectrum above 1 TeV. HESS reported a spectral fall at around 1 TeV with the change of the slope from 3.0 to 4.1. This is a fundamental issue, and LAT will be able to study the CRE spectrum above 1 TeV with Pass 8 analysis. Expected statistics from 1 to 3 TeV is $\sim 3,500$ electrons for 3 years if the spectral index does not change ($\sim 2,800$ if the spectral index above 1 TeV is 4.1 as reported by HESS)
4. CRE anisotropy. We already published anisotropy limits on the CRE flux. Currently the Fermi LAT sensitivity is approaching the range expected by the theoretical models, both for dark matter and for pulsars.

Stay tuned!

